BNL-94500-2010-CP

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SUBMITTED TO PHYSICAL REVIEW: SPECIAL TOPICS, ACCELERATORS AND BEAMS

December 2010

Photon Sciences Directorate

Brookhaven National Laboratory

U.S. Department of Energy
DOE – Office of Science

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INSTABILITIES RELATED WITH RF CAVITY IN THE BOOSTER SYNCHROTRON FOR NSLS-II

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Abstract

The booster synchrotron for NSLS-II accepts beam with 200 MeV from a linac and raises its energy up to 3 GeV. In order to raise beam energy up to 3 GeV, a 7-cell PETRA cavity is installed. Beam instabilities related to the cavity impedances are discussed. In particular, in order to avoid coupled-bunch instability, we consider that cooling water temperature for the cavity should be changed to shift frequencies of higher order modes (HOM) to avoid beam revolution lines. To obtain the relation between the temperature dependence of amount of frequency shift in each HOM and cavity body temperature, we carried out the measurement by changing cavity body temperature. From the measurement data, we calculate the required temperature variation. We summarize the results and describe the system design.

INTRODUCTION

National synchrotron light source-2 (NSLS-II) is a third generation synchrotron radiation facility and is just under construction at Brookhaven National Laboratory (BNL) [1]. The facility consists of three parts, a linac, a booster synchrotron and a storage ring. The linac supplies 200 MeV electron beam to the booster synchrotron, which raises the beam energy from 200 MeV to 3 GeV and transfers the beam to the storage ring. The storage ring stores the beam at 3 GeV and the maximum stored current designed is 500 mA. A fundamental radio frequency (RF) for the linac is 3 GHz. The booster synchrotron and the storage ring are operated at 500 MHz as a fundamental RF. Beam from the linac is stored in the booster ring in a short time within one second and is extracted toward the storage ring. The maximum charge per one injection supplied from the linac is 15 nC, whose value is so high that injection efficiency from the linac to the booster synchrotron gets worse because of space charge effect in the linac. In order to suppress the space charge effect, we set two-time beam injections. First beam with around half of 15 nC is injected into the booster ring from the linac and second beam with the same charge as the first one is injected in100 ms later. The booster ring, thus, stores the electron charge of 15 nC as a total charge, which corresponds to 28.5 mA as a current. A 7-cell cavity [2] is installed in order that the beam with 200 MeV is accelerated up to 3 GeV. In order to maintain the beam current stably from injection time to the beam extraction time in the booster synchrotron, we cannot help discussing about notorious beam instability problem, so we called “coupled bunch instability”. Since the 7-cell cavity has various frequencies of higher order modes (HOM) and also damping time due to synchrotron radiation loss is quite long at 200 MeV, we need to develop a method to suppress the coupled bunch instability. In this article, we are going to mention the suppression method as for coupled bunch instability due to the 7-cell cavity.

HIGHER ORDER MODES OF 7-CELL CAVITY

First of all, let us show the higher order modes (HOM) in the 7-cell cavity. We list up about various characters of HOM’s, such as frequencies, unloaded Q_0 values and shunt impedances R_{sh} (The circuit impedance R_a is related to the shunt impedance R_{sh}: $R_{sh}=2R_a$) in Table 1 [3]. Since the damping time in the minimum beam energy at the time of beam injection from the linac gives the longest one, the coupled-bunch instability easily occurs in the booster ring at that time. This is one of the most serious problems in the booster synchrotron. Since all parameters as for the beam are changed automatically in the duration of excitations of all magnets and RF cavity, we don’t need to care about HOM problem at all. When beam gains the energy of 3 GeV, all parameters become stable and HOM problem might appear at 3 GeV again. Thus we have to discuss the coupled-bunch instability problem particularly in the beam injection time from the linac and also in the beam energy of 3 GeV.

Table 1: HOM’s of 7-cell cavity

Mode	Frequency [MHz]	Q_0	R_{sh}[MΩ]
TM011(longitudinal)			
	722	32200	225.6
	728	33600	599.4
	733	35000	144.6
	738	35500	96.0
	739	36000	91.4
TM110(transverse)			
	860	55700	7.36
	867	56800	8.74
	869	58200	28.0
	871	59400	9.86
TM111(transverse)			
	1043	40400	41.8
	1046	40900	13.1
	1089	49400	8.5
TM021			
	1465	54600	7.76
TM012			
	1545	44300	13.4

Notification: TM012 was not observed using 7-cell cavity.
So we neglect this mode.

HOW TO SUPPRESS HIGHER-ORDER MODES PROBLEM

It seems that the shunt impedances as for TM011 mode are too high to store beam in the booster ring. However, the electric field of TM011 mode focuses on the top of a cavity, where an input coupler is installed. Thus electric field of TM011 is strongly coupled with an input coupler. Consequently the impedance of TM011 decreases automatically. The TM110 mode kicks beam transversely by the magnetic fields. On the other hand, TM111 mode kicks beam by the electric field. If the coupled-bunch instability of transverse modes occurs in an actual beam operation, we cannot add the beam anymore over the threshold current. In general, TM110 and TM111 are notorious modes as coupled-bunch instability. First of all, we calculate threshold currents due to HOM's.

THRESHOLD CURRENT

Let's calculate the threshold current in each mode. In order to calculate the threshold currents as for longitudinal and transverse HOM's, we assume that the theoretical threshold current is given by that the instability will arise if the growth rate exceeds the damping rate [4][5][6][7][8] and also we assume the beam has a rigid form. When higher-order modes just coincide with the revolution frequency, they are grown and kick stored beam. The revolution frequency is 1.894 MHz. If one of HOM's coincides with or is closes to the revolution frequency, beam with the energy of 200 MeV injected from the linac doesn't survive due to the coupled-bunch instability. The threshold currents concerning longitudinal and transverse modes are given by the following expressions of

$$I_{th}(longitudinal) = \frac{2 \cdot E_0 \cdot f_{sy}}{\tau_s \cdot e \cdot \alpha \cdot f_r \cdot f_{HOM} \cdot Z}, \qquad (3\text{-}1)$$

E_0:electron energy
f_{sy}:synchrotron frequency
τ_s:longitudinal damping rate
e: electron charge, e=1 we take natural unit
α: momentum compaction factor
fr: revolution frequency (=1.893 x 10^6 Hz)
f_{HOM}: HOM frequency
Z: impedance for HOM

$$I_{th}(transverse) = \frac{2E_0}{\tau_\beta \cdot e \cdot \beta_T \cdot f_r \cdot Z}, \qquad (3\text{-}2)$$

τ_β:transverse damping rate, $\tau_\beta = 2\tau_s$
e: electron charge, e=1 we take natural unit
β_T: beta-function.

If one of HOM's coincides with just the revolution frequency line, stored beam would be lost almost completely at the beam energy of 200 MeV. As an example, threshold currents for TM110 mode are calculated to be 65 nA at 200 MeV and 3.3 mA at 3 GeV, respectively. Basing on those threshold currents, we present the suppression method of coupled-bunch instability in the next section.

SUPPRESSION OF HOM PROBLEM

In order to store the beam current stably, we have to use a something HOM suppression methods. From the results of the threshold current given in the previous section, we show a method that makes impedances smaller by shifting the frequencies of HOM from the revolution frequency. To store beam current over 50 mA, we can obtain the required impedances from the both equations of (3-1) and (3-2), and result the values 2 ohms for TM011, 36 ohms for TM110 and 28 ohms for TM111, respectively. To reduce the values of those impedances, we detune the frequencies of HOM from the revolution frequency. We use unloaded Q_0 values in calculating the frequency shifts. The Q_0 value is expressed by using the resonant frequency f and Δf, which represents the full width at half maximum, Q=f/Δf. Let's assume Gaussian as the distribution function of impedances. Since the center of distribution function gives the maximum impedance, we can calculate the frequency shift. As for TM011 mode, the impedance becomes 2 ohms at the frequency shift of 56 kHz from the center of frequency. And also we can calculate the frequency shifts as for TM110 and TM111, and we get 33 kHz and 58 kHz, respectively. Thus we obtained required amount of frequency shifts as for HOM's. What we need the next is to obtain the relation between cavity temperature and frequency shift of each HOM. In order to obtain the relation between cavity body temperature and frequency shift of HOM, we carried out that we changed cooling water temperature for 7-cell cavity and took frequency shift for each HOM. When we change the water temperature, we adjusted the resonance frequency of cavity at the fundamental frequency of 499.67 MHz by using two movable tuners. And a typical data is shown in Fig. 1. However, we could not observe the mode of TM012 in Table 1. We finally obtained the relation between the cavity body temperature and frequency shifts of HOM's as shown in Fig. 2. We showed two cases of both without tuning at the fundamental frequency and with tuning.

From Fig. 2, we can know the frequency shifts of TM011, -10.1 kHz/degree for TM110, -13.2 kHz/degree for TM111 modes, -22.5 kHz/degree for TM021, respectively. In order to reduce those impedances, we can know better cavity body temperature. Taking into account of various conditions as for utility, we decided to set the cooling water temperature of 35 degrees. Let us plot all frequencies of HOM on the line of revolution frequency at the cavity body temperature of 35 degrees and we obtain the Fig.3. The numbers of points correspond to the frequencies of HOM's. The frequency differences between revolution lines and (1) and (13) are 59 kHz and 100 kHz, respectively.

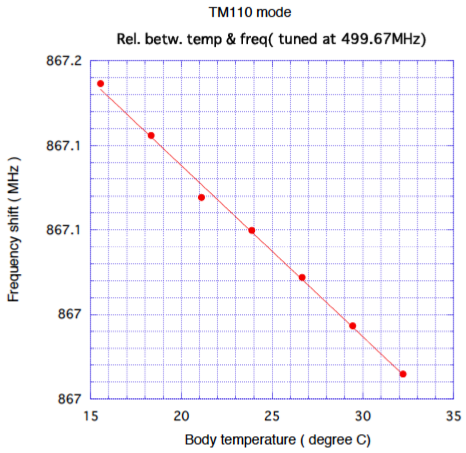

Figure 1: Relation between cavity body temperature and frequency shift of TM110 mode.

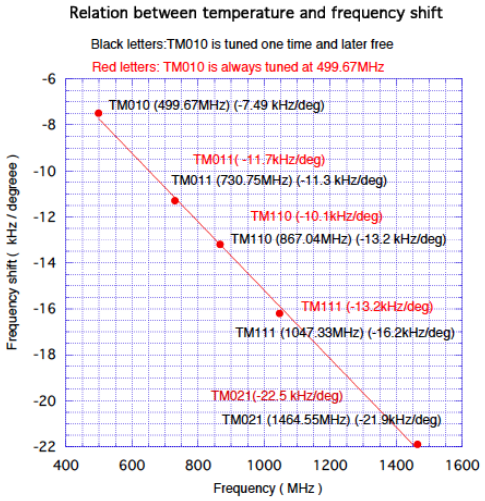

Figure 2: Relation cavity temperature and frequency shifts as for various HOM's. The red line tells that cavity is not tuned at the fundamental frequency.

Even if one of the frequencies of HOM's meets the revolution lines, we can change the cooling water temperature to avoid HOM issue. The required range of water temperature can be calculated using the data as shown in Fig. 2. We show the calculation results; 4.8 degrees for TM011, 3.6 degrees for TM110 and 4.4 degrees for TM111, respectively. Thus the calculation obtained above says that the required range of water temperature is 35±5 degrees. We also have to mention in case of the beam energy of 3 GeV. The temperature raise of the cavity is estimated to be around 1 degree. Even if body temperature is warned up by 1 degree, the frequency shifts for HOM's are smaller enough than 59 kHz, which just corresponds to the difference between the revolution line and the number (1) of TM110. So we expect that we would completely suppress the coupled-bunch instability problem.

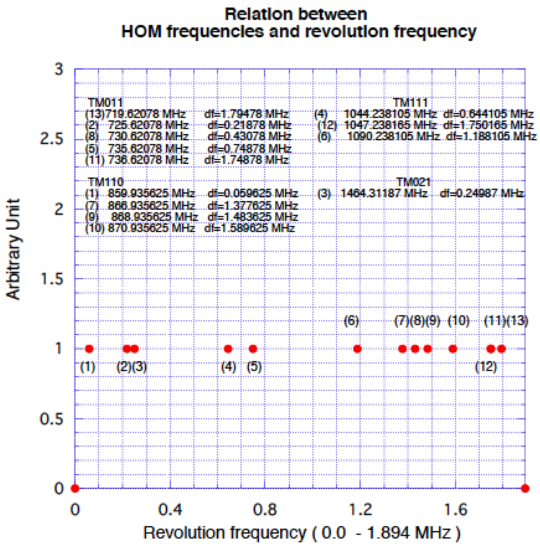

Figure 3: Relation between HOM's and revolution frequencies

SUMMARIES

A 7-cell cavity is installed in the booster synchrotron to raise the beam energy from 200 MeV to 3 GeV. Since the damping time at the beam energy of 200 MeV is quite long, coupled-bunch instability might be induced. To avoid the problem, one method is to make the shunt impedances of HOM smaller by changing the cavity body temperature. We conclude that we set the cooling water temperature at 35±5 degrees to do stable operation without beam loss due to cavity.

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